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Software-Defined Transceivers in Dynamic Access Networks

David Hillerkuss and Juerg Leuthold

***Abstract*— Software-defined transceivers offer flexibility, increased resilience to channel impairments, and an upgrade path for future transmission systems. Such transceivers have been discussed in literature for several years and are now about to be established in long-haul optical communications. In access networks however, the circumstances are different. Here, a great variety of transceiver and network architectures has been developed. The hardware implementations impose various limitations on the benefits that are usually associated with software-defined transceivers. So the question is: Will software defined transceivers be of equal importance in dynamic access networks? And, as fundamental limitations mainly originate in the modulation and detection techniques, which hardware implementations would be most promising for software-defined transceivers?**

***Index Terms*— Optical fiber communication, Optical modulation, Optical receivers, Optical transmitters, Transceivers.**

I. Introduction

SOFTWARE-DEFINED TRANSCEIVERS (SDTs) are transmitters and receivers where the digital signal processing unit can be flexibly reconfigured to transmit and receive different signals [1, 2]. SDTs may further increase the flexibility in future software-defined networks (SDN) [3] as they can adapt to channel conditions and bandwidth requirements [4]. For this, the digital signal processing allows to flexibly transmit subcarrier multiplexed signals [5-8], adapt transmission formats [9, 10], as well as pulse shapes and frequency responses [7, 10, 11].

Having matured in the past years, SDTs are now about to be established in long-haul optical networks [2]. Recently, it has been suggested that SDTs will also play an important role in the development of dynamic access networks [12, 13]. In contrast to SDTs in long-haul networks that are mostly based on coherent transceivers, SDTs in access networks come with a large variety of hardware configurations. And indeed, a great variety of access network transceiver implementations have emerged that show a trend towards a flexible use of modulation formats and multiplexing schemes.

A good example for the benefits of advanced modulation formats in access networks is demonstrated in refs. [14, 15]. In these references, advanced modulation formats facilitate seamless, backward compatible upgrades from existing time division multiplexing (TDM) access networks to next generation passive optical networks (NG-PON2). More precisely, the networks can be upgraded gradually by serving new customers with phase-shift keying rather than on-off keying. This way the data rates can be increased by a factor of 3 or 4.

Other examples show how increased flexibility can be obtained by replacing single carrier by multi-carrier multiplexing schemes. Orthogonal frequency division multiplexing (OFDM) [16-18] and Nyquist frequency division multiplexing (NFDM) [19-21] have already been demonstrated. In such schemes, sub bands of the multiplexed signals can be allocated flexibly to users with different demands [19-22]. An advantage is, that the optical network units (ONUs) only needs to process the sub band of the spectrum that has been allocated – and since this typically is a small fraction of the total spectrum, the required electrical bandwidth is low. This allows for cheap ONUs. Conversely, the OLT is more expensive. But as it is shared among hundreds to thousands of users [23], it can utilize more expensive components with large electrical bandwidths and higher power consumption. Using subcarrier multiplexing has more advantages. For example, the data rates for standard components can be increased significantly by using carrierless amplitude and phase modulation (e.g. 4 bit/s/Hz spectral efficiency [24]) or even carrier dependent bit-loading, e.g. enabling >100 Gbit/s transmission with 10 GHz class directly modulated lasers (DMLs) [25].

Hardware platforms for future SDTs in access networks might come in a large variety of flavors that offer a different degree of flexibility. They might be based on transmitters allowing for the encoding of real-valued modulation of

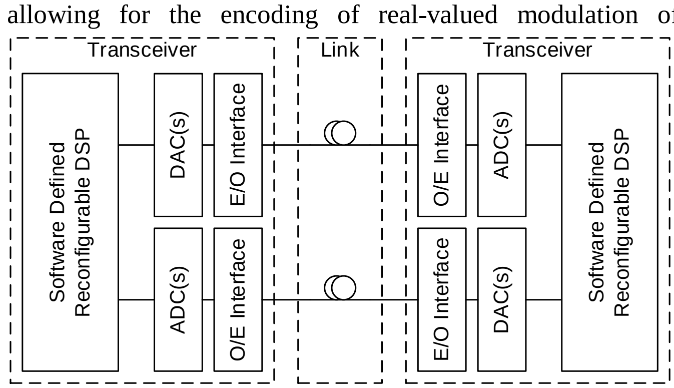

Fig. 1. Concept of software defined optical transceivers. Each transceiver combines the physical interface for the respective transmission system with a software defined reconfigurable digital signal processing (DSP).

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David Hillerkuss and Juerg Leuthold are with the Institute of Electromagnetic Fields (IEF), ETH Zurich, Zurich, 8008, Switzerland

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amplitude or intensity [16, 17, 20, 22, 24-27] or even complex modulation [14, 15, 18-21, 28-32]. Receivers might use direct [14, 15, 24-27], heterodyne [16, 19, 20, 28, 29, 31, 32], or coherent/intradyne detection [14-20, 22, 30, 32]. Common for all SDTs though is the flexible reconfiguration of the digital signal processing unit.

In this paper, we will first provide an overview over the different modulation and reception schemes that can be used for flexible optical transceivers. We will then evaluate the advantages and drawbacks of the different approaches in flexible optical networks with changing routes, bandwidths, and modulation formats. Finally, we will summarize and provide a view on what transceiver concepts are to be expected in future dynamic access networks. The paper is based on our conference contribution [33] and has been extended to provide a more complete overview on transmitter and receiver schemes.

II. Modulation and Reception Schemes for Software-Defined Transceivers

In access networks one currently finds a large number of hardware configurations. Fig. 2 and Fig. 3 give an overview on some of the main modulation and detection schemes. In the following, we will derive a comparison between these schemes to clarify the main advantages and challenges for all these schemes.

To perform a fair comparison, we assume a fixed analog-to-digital and digital-to-analog converter (ADC/DAC) bandwidth and sampling rate. This defines electrical transmitter and receiver bandwidths. Transmitters with directly modulated lasers and receivers with direct detection will serve as a reference case for all evaluations. Higher order intermodulation products generated by nonlinearities or intensity modulation are neglected in this discussion.

A. Comparison of Transmitter Hardware Platforms

We first compare six modulation approaches based on direct, external, and complex modulation in Fig. 2(a-f).

Directly modulated lasers allow for the simplest scheme as they require the minimum number of optical components, Fig. 2(a). Nevertheless, in experiments, directly modulated lasers have transmitted data rates beyond 100 Gbit/s [25]. Directly modulated lasers are a standard in optical access networks and the subsequent solutions will be compared against it.

An external modulator can improve the quality of the transmitted signal, Fig. 2(b). Such an external modulator can not only encode information without chirp but also shape the transmitted pulse. External modulators have a well-known transfer function and allow the generation of several amplitude modulation formats [34]. So for instance, such modulators enable transmission of advanced formats like duobinary [35], which allows for encoding with higher spectral efficiency [35], carrier-suppressed return-to-zero (CSRZ), which offers reduced nonlinear crosstalk [36], and alternate-mark inversion, which reduces intersymbol interference [37]. Using duobinary, external modulators have been used for access network demonstrations at highest symbol rates [38].

A precise optical filter with a sufficiently steep edge can remove the redundant information in the second sideband [39],

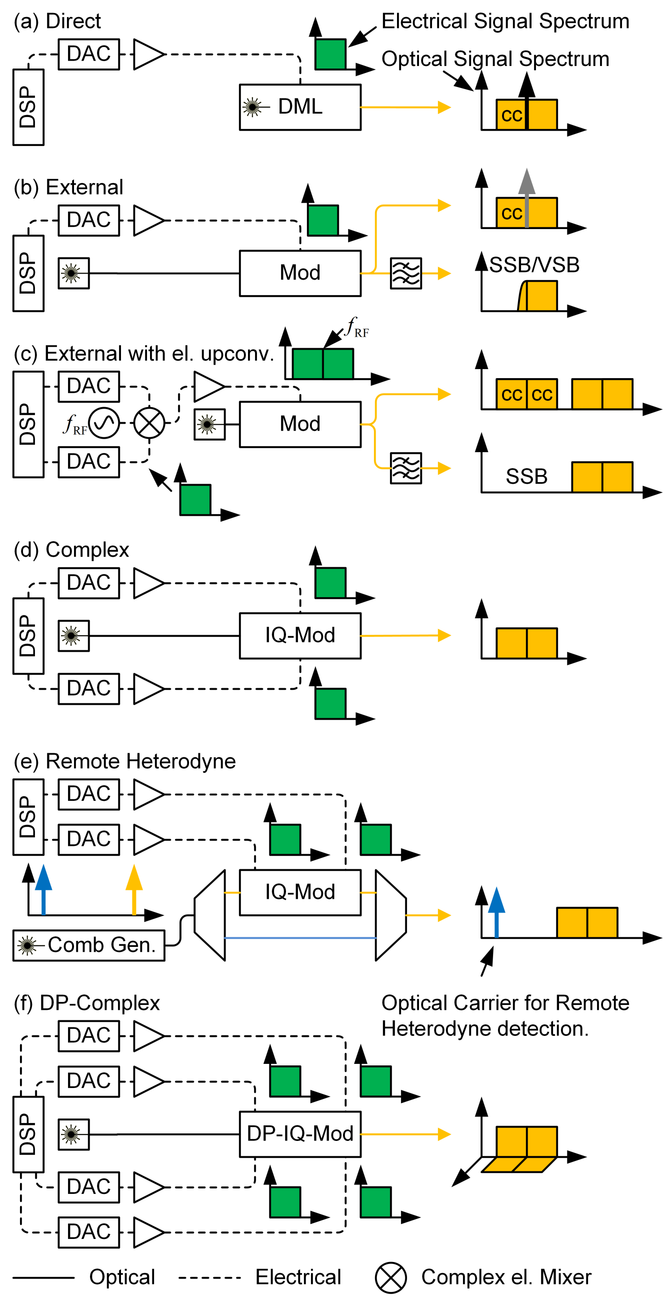

Fig. 2. Conceptual representation of modulation schemes for optical transmission with abstracted spectra. (a) Intensity modulation (IM) with directly modulated laser (DML) by modulation of the laser current with a real-valued signal. The output signal spectrum consists of a carrier (black arrow) together with the modulation sidebands. Left and right sideband contain redundant information (marked by cc). (b) IM or amplitude modulation (AM) with an external modulator (MOD). In case of bipolar AM, no carrier is observed (grey arrow). Single sideband signals (SSB) are generated by filtering one of the redundant cc sidebands. (c) Electronic upconversion to an electronic carrier frequency f_{RF} before modulation generates signals with a larger bandwidth. An additional guard band is inserted to simplify SSB filtering (d) Complex modulation with an external IQ modulator (IQ-Mod), both sidebands contain independent information. (e) A second laser line (blue arrow) is added to the complex modulated signal to enable remote heterodyne detection. This way, a complex modulated signal can later on be detected without polarization tracking using only a photodetector. (f) Dual-polarization complex modulation with a dual polarization IQ-modulator. Higher order intermodulation products generated by nonlinearities or intensity modulation are neglected in this representation.

generating single sideband signals (SSB) and thereby in the ideal case increase the spectral efficiency by a factor of two, see

Fig. 2(b). Due to the limited precision of standard optical filters, the redundant information often can't be removed completely. However, partial filtering of the sidebands is more practical and allows the encoding of what is known as the vestigial sideband (VSB) format [40]. VSB is advantageous as it offers good suppression of intersymbol interference and low nonlinear crosstalk in combination with a very narrow spectrum [40]. Rather than with filters, SBB can also be generated using a dual drive Mach-Zehnder modulator utilizing the phasing method also known as Hartley technique [41].

Electronic upconversion in an electronic mixer can generate electrical signals with twice the bandwidth, Fig. 2(c). In addition, this technique allows for the insertion of a guard band in between both optical sidebands to allow for effective SSB filtering. As a price to pay, such schemes need driver amplifiers and modulators with more than twice the bandwidth.

In contrast to intensity and amplitude modulation, complex modulation in an IQ-modulator directly increases the data rate by a factor of 2 for a given bandwidth of the DAC, Fig. 2(d). Due to the complex modulation, left and right-hand modulation sideband are no longer coupled, the spectral efficiency can be increased by a factor of two without the use of additional optical filter.

Transmitters for remote heterodyne detection transmit a complex modulated signal in conjunction with a carrier for mixing at the receiver [42], Fig. 2(e). As this carrier traverses the same optical transmission link as the signal, usually no polarization tracking is required at the receiver. Such a carrier can be generated in several ways: By a second laser, in a comb generator [42] as illustrated in the Fig. 2(e), or even through digital signal processing [18]. Due to the complex modulation, the scheme can transmit twice the data rate of a direct modulation system and as this is a coherent transmission scheme, transmission is not limited by chromatic dispersion. However, due to the additional carrier and the guard band for the remote heterodyne detection, the spectral efficiency remains that of a direct detection system.

Polarization multiplexing in conjunction with complex modulation offers four times the data rate and spectral efficiency of a direct modulation system. It is therefore the most spectrally efficient scheme, however, it also utilizes the largest number of components.

TABLE I shows a summary of the compared parameters of the transmitters: the relative signal bandwidth and the spectral efficiency gain.

TABLE I
COMPARISON OF SDT TRANSMITTER HARDWARE PLATFORMS

Scheme	Direct	Ext.	Ext. with el. upconv.	Complex	Remote Hetero-dyne	Dual Pol. Complex
Signal BW. Gain	1	1	2	2	2	4
Spectral Eff. Gain	1	1 SSB: 2	1 SSB: 2	2	1	4

Comparison of SDT transmitter hardware platforms for fixed given ADC and DAC specifications. Relative signal bandwidth gain and spectral efficiency gain in relation to an intensity modulation hardware platform.
(SSB – single sideband signal)

B. Comparison of Receiver Hardware Platforms

When comparing receiver hardware platforms, it becomes clear that the chosen receiver platform plays an even more important role for the transmission link performance: It not only sets limits to the relative signal bandwidth and spectral efficiency, but also influences the dispersion tolerance of the transmission link and defines if the receiver offers wavelength selectivity. Dispersion tolerant transmission schemes allow for long and even changing transmission distances without the need for optical dispersion compensation. Wavelength selective receivers enable the processing of a particular channel from within a wavelength multiplexed signal without prior optical filtering. Fig. 3 shows some of the main receiver schemes.

Direct detection allows signal reception with the least amount of components at the lowest price. Yet, direct detection schemes need chromatic dispersion compensation if the signal bandwidth and transmission distance should not be limited [43]. Such limitations can in part be overcome by optical dispersion precompensation in the transmitter as in a recent 40 Gbit/s access network experiment [38]. Still, such a system will only operate within a limited distance range where the residual dispersion is small. Also, it has to be readjusted each time the network changes, which is an issue for flexible networks. However, this restriction can be lifted with a coherent detection scheme as discussed below. As a direct detection receiver utilizes a single photodetector to measure the incident optical power, it is inherently colorblind and therefore has to rely on filters to select the received channel in a wavelength multiplexed system. It should be mentioned though, that the phase- and frequency-independent nature is also one of the biggest advantages of direct detection systems, as the optical frequency and phase noise do not need to be estimated and corrected in digital signal processing. In such systems, the main impairment in addition to noise is the sampling clock frequency drift and clock phase noise, which can be compensated either by an electronic clock recovery or in digital signal processing.

In coherent heterodyne detection, the signal is mixed with a laser line that is separated by a guard band from the signal band, see Fig. 3(b). The guard band is needed to avoid overlap of the desired receiver signal with the additional mixing products. In our illustration, the desired signal is the mixing product of the local oscillator with the signal and it is shown as the green spectrum in Fig. 3(b). The undesired mixing products of the signal with itself are shown in red. The heterodyne receiver can be classified in two types: A scheme without electronic downconversion Fig. 3(b) [18, 28], and a scheme with electronic downconversion, Fig. 3(c) [19, 20, 29].

The scheme without electronic downconversion can only use half of the available ADC bandwidth for signal reception. The other half of the bandwidth is lost for the guard band. To be fair, one should mention though that the spectral occupation in the network is halved as well. The hardware requirements for the receiver electronics are actually similar to those of a direct detection scheme. The only additional component is the laser for the mixing process. If the laser line for mixing is generated at the receiver, it can be used to select the received optical channel without an additional optical filter [28]. In such a system, however, digital signal processing will have to estimate and compensate for the laser frequency drift and phase noise of

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transmitter and receivers [44]. Also, as the laser polarization is not aligned to the received signal, polarization tracking or more likely a dual polarization setup [28] is required to implement a polarization independent receiver. Such a dual polarization receiver then requires additional digital signal processing algorithms for polarization demultiplexing and equalization [44]. A dual polarization setup and polarization tracking can be avoided if the laser line for mixing is sent through the transmission fiber with the signal in the so-called remote heterodyne scheme [42]. These systems offer the advantage that optical phase noise and frequency drifts cancel out, leading to a reduced signal processing complexity.

Electronic downconversion of the signal in a mixer allows to exploit the full ADC bandwidth for signal reception as no bandwidth is lost for a guard band, see Fig. 2(c). In this scheme the signal is received with a photodiode that has up to four times the bandwidth of the ADC and is then down-converted in a complex mixer. An additional ADC is needed to detect the signal from the complex electrical mixer. With such a scheme one can receive signals with twice the bandwidth of a direct detection receiver or four times the bandwidth of the scheme without electronic downconversion. The electronic downconversion scheme can also be an attractive solution to directly access a subband by tuning the electronic local oscillator to a particular frequency. This reduces cost, digital signal processing complexity and ADC requirements [19, 20, 29].

In the case of coherent/intradyne detection, the received bandwidth for a given ADC is increased by a factor 2 compared to direct detection. A single polarization scheme, see Fig. 2(d), will again require polarization tracking as the local oscillator has to be aligned to the received signal. A dual polarization scheme requires no polarization tracking and allows for polarization multiplexing, Fig. 2(e). Polarization multiplexing provides another factor of 2 in signal bandwidth. However, this comes at the price of a total of four ADCs in the receiver and the requirement for complex digital signal processing. The digital signal processing includes timing, frequency, and phase estimation, as well as the digital signal processing algorithms for polarization demultiplexing and equalization [10, 44]. One of the biggest advantages is that such a receiver will be able to tune in on individual frequency bands using the tunable local oscillator [22].

TABLE II shows a summary of the discussed parameters of the receiver: the relative signal bandwidth, the spectral efficiency gain, and the dispersion tolerance of the schemes.

TABLE II
COMPARISON OF SDT RECEIVER PLATFORMS

Scheme	Direct	Hetero-dyne	Heterodyne with el. downconv.	Intradyne
Signal bandwidth gain	1	1/2 (SP) 1 (DP)	2 (SP) 4 (DP)	2 (SP) 4 (DP)
Spectral efficiency gain	1	1 (SP) 2 (DP)	1 (SP) 2 (DP)	2 (SP) 4 (DP)
Dispersion Tolerance	No	Yes	Yes	Yes
Wavelength selective	No	Yes / No (RH)	Yes / No (RH)	Yes

Comparison of SDT receiver hardware platforms for fixed given ADC and DAC specifications. Relative signal bandwidth gain, spectral efficiency gain in relation to a direct detection hardware platform. With: SP - single polarization, DP – dual polarization, and RH – remote heterodyne.

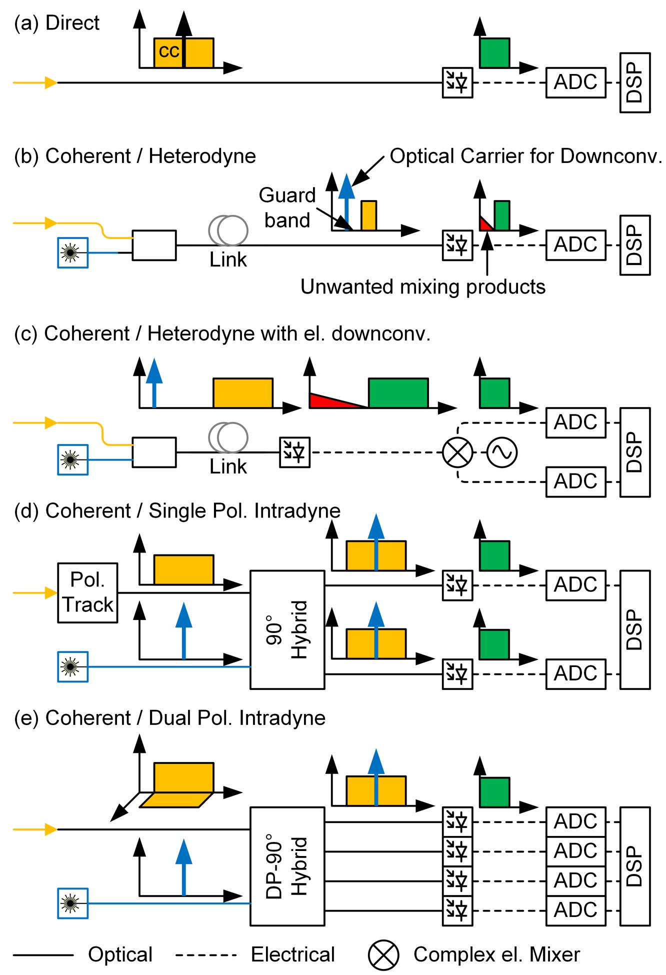

Fig. 3. Conceptual representation of receiver schemes for optical signals with abstracted spectra. (a) Direct detection of an intensity modulated signal. (b) Heterodyne detection by combining the incoming signal (orange) with a local oscillator (blue) and mixing in the square-law photodetector. The carrier is often sent along with the signal to avoid polarization tracking (remote heterodyne). The guard band is chosen such that it avoids an overlap of the received signal (green) with the mixing products of the signal with itself (red) (c) Detection similar to (b), followed by an electrical down conversion to avoid processing of the guard band. (d) Coherent/intradyne reception down converts the incoming signal directly to the baseband. (e) Coherent / dual polarization intradyne reception allows for reception of signals with polarization multiplexed signals and down converts the incoming signal directly to the baseband. In all cases, electrical bandwidth and sampling rate of digital-to-analog and analog-to-digital converters (DAC/ADC) are assumed to be the same. Transmitter and receiver use digital signal processing (DSP). Discrepancies in the received signal bandwidth stem from the different receiver schemes. Higher order intermodulation products generated by nonlinearities or intensity modulation are neglected in this representation.

C. Discussion of Hardware Platforms

The transmitter scheme mostly defines the available signal bandwidth and the spectral efficiency during data transmission. Both are increased by complex modulation and/or polarization multiplexing. Highest efficiencies are achieved by complex modulation in combination with polarization multiplexing.

The receiver scheme is more critical as imposes limitations on the data rate, spectral efficiency, dispersion tolerance and the usability in wavelength multiplexed systems. Direct detection is cost efficient, but the transmission distance will be limited by the available optical dispersion compensation. Flexible optical networks, where optical paths can be reconfigured require flexible dispersion compensation, which is offered by coherent detection schemes. Among the coherent schemes, remote heterodyne detection has an advantage in that it has the lowest additional complexity and requires no local laser at the receiver. However, the spectral efficiency is not improved in comparison to a direct detection system. Also the receiver is not wavelength selective and therefore requires an additional filter in wavelength multiplexed systems. This can be solved by implementing a tunable laser in the receiver for coherent detection. Due to the resulting polarization selective behavior of the receiver, the implementation of polarization multiplexing is desirable to avoid polarization tracking, effectively also increasing spectral efficiency. Conversely, coherent/intradyne schemes offer an additional gain in spectral efficiency when compared to other schemes. Coherent receiver schemes are of particular interest in access networks as they combine the additional flexibility for subband access and wavelength selection through tuning of the local oscillator besides a compatibility with any modulation format and multiplexing scheme.

III. Benefits of and Requirements for Software Defined Transceivers

Software defined transceivers (SDTs) offer increased flexibility through reconfigurable signal processing. Software defined transmission is a concept that is independent of the underlying hardware platform. Yet, depending on the hardware platform a SDT can be more or less versatile. A common feature of SDTs is the ability to flexibly adapt the modulation format to the capacity requirements and the transmission characteristics of the network. More recent SDTs can also handle subcarrier multiplexing. Flexibility in subcarrier multiplexed systems then means reconfiguration with respect to the number of subcarriers, their bandwidth together with bitloading and powerloading functionalities [25]. As formats and transmission schemes are no longer fixed, a control channel for reconfiguration or modulation format recognition will be required for synchronization of the SDTs. These capabilities are also required for SDTs to adapt to changing network requirements and channel conditions.

IV. Conclusions

Software defined transceivers (SDTs) can utilize all hardware platforms and transmission schemes, however, not all transmitter receiver combinations benefit to the same extent. There are three groups of hardware platforms that benefit differently: The intensity modulation and direct detection systems, the coherent systems with single polarization receivers, and the coherent systems with dual polarization receivers.

Independent of the scheme, SDTs offer increased flexibility as they permit to adapt data rates and to allocate channel bandwidths upon need. In addition, they allow to maximize the data throughput by adapting the transmission format, pulse shape, frequency response and subcarrier multiplexing scheme to a given electrical bandwidth and channel characteristics. We therefore expect software defined transceivers to play a vital role in harnessing the ultimate performance reserves of most communication systems.

Utilizing coherent communication schemes in addition, offers flexibly in compensating for dispersion and may offer higher sensitivity (the actual sensitivity depends on the implementation). Therefore, we expect that coherent detection systems will replace direct detection systems in most cases where chromatic dispersion can make an impact. Due to a lower complexity of the optical components, heterodyne systems are likely to serve as an intermediate step, paving the way towards full complex modulation and dual-polarization intradyne detection systems.

Full coherent schemes with complex modulation and dual polarization receivers provide an up to 4-fold increase in available communication bandwidth over direct detection. Due to these advantages in flexibility and compatibility as well as the advancements in photonic integration, we expect that the majority of future software defined transceivers for access networks are likely to utilize complex modulation and coherent/intradyne reception.

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